Renewable and Sustainable Energy Reviews 13 (2009) 2716–2721

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy, economics and environmental impacts of renewable energy systems

Varun [a,*], Ravi Prakash [b], Inder Krishnan Bhat [a]

[a] National Institute of Technology, Hamirpur 177005, HP, India
[b] Motilal Nehru National Institute of Technology, Allahabad 211004, UP, India

ARTICLE INFO

Article history:
Received 15 May 2009
Accepted 29 May 2009

Keywords:
Greenhouse gas
Energy pay-back time
Electricity
Emissions
Renewable energy

ABSTRACT

The renewable based electricity generation technologies were assessed against a range of sustainability indicators using data obtained from the literature. These indicators are cost of electricity generation, greenhouse gas emissions and energy pay-back time. All the three parameters were found to have a very wide range for each technology. For grading different renewable energy sources a new figure of merit has been proposed, linking greenhouse gas emissions, energy pay-back time and cost of electricity generated by these renewable energy sources. It has been found out that wind and small hydro are the most sustainable source for the electricity generation.

Contents

1. Introduction

Energy is a vital element in human life. A secure, sufficient and accessible supply of energy is very crucial for the sustainability of modern societies. The demand for the provision of energy is increasing rapidly worldwide and the trend is likely to continue in future. In 2005, the worldwide electricity generation was 17450 TWh out of which 40% originated from coal, 20% from gas, 16% from nuclear, 16% from hydro, 7% from oil and only 2% from renewable sources i.e. small hydro, wind, geothermal, etc. [1]. Electricity producing systems presently in use across the world can be classified into three main categories: fossil fuels, nuclear power and renewables. Fossil fuels in their crude form, i.e. wood, coal and oil have traditionally been an extensive used energy resource. Nuclear power due to a number of reasons is not accessible to the vast majority of the world and has found its application only within developed countries [2]. Renewable energy resources are easily accessible to mankind around the world. Renewable energy is not only available in a wide range, but are also abundant in nature. Renewable energy sector is meeting at present 13.5% of the global energy demand. Renewable energy sector is now growing faster than the growth in overall energy market. Some long-term

* Corresponding author. Tel.: +91 1972 254742.
E-mail address: varung@nitham.ac.in (Varun).

1364-0321/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2009.05.007

scenarios postulate a rapidly increasing share of renewable technologies (made up of solar, wind, geothermal, modern biomass, as well as the more traditional source i.e. hydro). Under these scenarios, renewables could meet up to 50% of the total energy demand by mid-21st century with appropriate policies and new technology developments [3].

Coal based electricity generation plants are known to have the highest CO_2 emissions per kWh electrical as well as other pollutants at high levels, but still it dominates the market due to its low cost of electricity generation and high availability of raw material. If significant efforts are not made to reduce the amount of emissions produced then the number of coal based power stations will continue to rise in developing countries [4].

The main activities associated with greenhouse gas (GHG) emissions from the energy sector includes: transport, electricity generation, manufacturing industries and construction and also substantial amount of energy usage in the residential, commercial and institutional sub-sectors, agriculture, forestry and fishing activities. India is expected to have a high growth rate in energy demand over the coming years due to its huge population and rapid economic development. India accounted for 3.5% of world primary consumption and 12% that of total energy consumed in Asia-Pacific region in 2002 [5].

Significant research has already been carried out for understanding the impact of electricity generation on the environment and economy. Several authors have conducted full life cycle analysis (LCA) of individual electricity generation technologies. Solar and nuclear based electricity generation technologies often are deemed to be "carbon free" because their operation do not generate any greenhouse gas. However, this is not so when considering their entire life cycle of energy production, it has been found out that GHG emissions and energy flow throughout the stages of the life of renewable and conventional electricity generation technologies. Switching to renewable energy sources for electricity generation provides beneficiary management strategies from the economic, as well as environment point of view. Renewable energy technologies are very important and should be recommended once the availability of various renewable sources is proven and the cost of such technologies become competitive which is already true for many applications.

The work presented in this paper seeks to access the performance of renewable energy technologies based upon energy, environment and economics. The selected renewable based electricity generation technologies are solar photovoltaic (PV), small hydro, wind and solar thermal. For PV and wind system most of the emissions are the result of electricity use during manufacturing. In these cases, an average grid mix for the region of manufacture is typically used to calculate energy use and emissions. Most work seeks to quantify parameters such as GHG emissions [6–10], energy pay-back time [11–12], and the cost of electricity generation [13–14]. The previous LCA studies on electricity generation used one or more indicators i.e. GHG emissions, acidification potential, energy intensity or energy pay-back time. These previous studies discuss the variation of results in different indicators for the electricity generation technologies but very few studies is reported in which stated three indicators has been used simultaneously [15–16]. Based upon these three indicators, a figure of merit (FM) has been proposed and based upon this figure of merit, sustainability of renewable based electricity generation technology has been estimated.

2. Sustainability indicators of renewable energy technologies

2.1. Energy pay-back time

Energy pay-back time (EPBT) means years to recover primary energy consumption throughout its life cycle by its own energy production. The total energy requirement of the electricity generation system and the annual power generated are concerned with the primary energy. To convert the annual power generation (kWh_e) to primary energy, there is a need for the average efficiency of the electricity generation projects in the studied country. Estimation of energy pay-back time is shown by Eq. (1).

$$\text{EPBT (years)} = \frac{\begin{array}{c}\text{Total primary energy requirement of}\\ \text{system throughout its life cycle (GJ)}\end{array}}{\begin{array}{c}\text{Annual primary energy generation}\\ \text{by the system (GJ/year)}\end{array}} \tag{1}$$

2.2. GHG emissions

Greenhouse gas emissions (gCO_{2eq}/kWh_e) were generally estimated according to the full operational life cycle of each renewable energy sources from the manufacturing of the plant to full operation of the system (birth to grave). These emissions are found to vary widely within each technology. For PV and wind energy system most of the emissions are the electricity usage during manufacturing. In these cases, an average grid mix for the region of manufacturing is typically used to calculate emissions. Estimation of greenhouse gas emissions is shown by Eq. (2).

$$\text{GHG emissions} = \frac{\begin{array}{c}\text{Total } CO_2 \text{ emissions throughout}\\ \text{its life cycle } (gCO_{2eq})\end{array}}{\begin{array}{c}\text{Annual power generation } (kWh_e/\text{year})\\ \times \text{ lifetime (year)}\end{array}} \tag{2}$$

2.3. Cost of electricity generation

An average cost of production of electricity over the full life cycle of each generation technology accounting for construction, installation, operation, maintenance, decommissioning, recycling/disposal. Intermittent renewable sources, i.e. PV and wind may require back up but these have not been included in cost calculations. Wide ranging values for the cost are seen for all the systems. Among all renewable sources, PV system has the widest range of cost for electricity generation due to various type of solar cells, and location specific variations, i.e. solar radiation intensity and electricity cost to manufacture cells. The cost of electricity generation has been reported in cents/kWh_e prevalent in US and/or European Union. For purpose of calculations, the US currency has been taken equivalent to euro, as the two currencies have nearly the same value and the level of development in US and European Union is comparable. Estimation of cost of electricity generation is shown by Eq. (3).

$$\text{Cost of electricity generation} = \frac{\text{Annualised expenses of the system (cent/year)}}{\text{Annual eleltricity generation by the system } (kWh_e/\text{year})} \tag{3}$$

3. Renewable electricity generation sources

3.1. Wind energy system

Wind energy uses the kinetic energy of the wind to produce a clean form of energy without producing contamination or emissions. Wind energy accounts for around 0.3% of the global installed electricity generation capacity due to its relatively recent emergence but due to its intermittent nature, it supplies around only 0.1% of total global electricity [17]. The installed capacity of wind power has been rapidly increasing during recent years

Table 1
Sustainability indicators for wind energy systems.

S. no.	Year	Location	Power rating (kW)	Life (years)	EPBT (years)	GHG emissions (gCO_{2eq}/kWh_e)	Cost (US cent/kWh_e)
1.	1997 [22]	Denmark	30	20	0.39	16.5	NA
2.	1996 [23]	Japan	100	20	NA	123.7	NA
4.	1999 [24]	India[a]	1500	20	1.0	19	NA
5.	1996 [25]	UK	6600	20	NA	25	NA
6.	2001 [26]	Japan	100	25	1.4	39.4	NA
7.	2005 [6]	Japan	300	NA	NA	29.5	NA
8.	2007 [27]	Turkey	22.5	25	1.4	20.5	5-74

[a] Mean value.

Table 2
Sustainability indicators for PV systems.

S. no.	Year	Location	Type of cell	Life time (years)	Power rating (kW)	GHG emissions (gCO_{2eq}/kWh_e)	EPBT (years)	Cost (US cent/kWh_e)
1.	2006 [29]	UK	mc-si	NA	14.4	44	8	NA
2.	2000 [30]	India	c-si	20	.035	300	NA	NA
3.	2000 [31]	Italy	c-si	30	3300	60	3.2	NA
4.	2000 [31]	Italy	a-si	30	3300	50	2.7	NA
5.	1997 [6]	Japan	c-si	20	3	91	15.5	NA
6.	2008 [15]	China	c-si	30	100000	12.1	1.9	19–20
7.	2006 [16]	Singapore	c-si	25	2.7	165	4.5	57
8.	2008 [15]	China	c-si	30	100000	9.4	1.5	19–20
9.	2008 [15]	China	a-si	30	100000	15.6	2.5	19–20
10.	1995 [32]	India	c-si	NA	35 kWh_e/m^2	NA	3.95	NA

especially in Denmark, Germany and Spain. In last years the installation of wind farms has experienced an exponential growth: the cumulative wind power capacity in the European Union raised to 34,205 MW at the end of 2004, up from 439 MW at the end of 1990 [18]. The world energy council has estimated that new installed wind capacity worldwide will reach 180–476 GW by the year 2020 [19].

The cost of wind generated electricity over years from 1980 to 2005 has fallen from 20 to 3.7 euro cents in large-scale systems [20–21]. Although there are several analysis about environment impact of renewable energy but not many LCA studies exist on high rated power generated by wind turbines. The cost of wind turbines continues to fall as more new capacity is installed. In high wind areas, wind power is competitive with other forms of electricity generation at between 3 and 5 cents/kWh_e. The global average price is expected to drop to 2.7–3 cents/kWh_e by around 2020 due to economics of scale from mass production and improved turbine designs. Table 1 shows the sustainability indicators for wind energy systems.

3.2. Solar photovoltaic (PV) system

Solar photovoltaic technology enables direct conversion of sunlight into electricity through semi-conductor devices called solar cells. Solar cells are interconnected and hermetically sealed to constitute a photovoltaic module. The photovoltaic modules are integrated with other components such as storage batteries to constitute solar PV systems and power plants. Photovoltaic systems and power plants are highly reliable and modular in nature. Solar radiation as intercepted at the earth's surface may be reasonably high in many regions but the market potential for its capture is low due to the current relatively high costs of solar panels. The cost of PV around 5000 USD/kW_e installed is slowly falling due to manufacturing scale up and mass production. Ita et al [15] compared 100 MW very large-scale power generation systems installed in the Gobi desert using five types of PV module; multi-crystalline a and b with 12.8% and 15.8%, amorphous silicon with 6.9%, cadmium tellurium (CdTe) with 9% and copper indium selenium (CIS) with 11% efficiency. Globally, the PV industry has grown rapidly, with an estimated 1.5 GW installed in 2005 [28]. Most of this growth has come from grid-connected systems, though the off-grid market has also continued to expand. The high cost of PV cells and its associated BOS (balance of system) constitutes one of PV's main present handicaps. Table 2 shows the sustainability indicators for solar PV systems.

3.3. Solar thermal system

Solar thermal electricity generation technologies can be categorized, i.e. parabolic trough, central receiver, paraboloidal dish, solar chimney and solar pond. Solar electricity generating units are designed generally in a power range of 30–150 MW [33]. In parabolic trough solar electricity generation system, solar receiver consists of a large array of parabolic trough reflectors that reflects the sunlight to a black absorber tube (lies in the focus line). The absorbed tube is cooled by a heat transferring fluid and this fluid (hot) is pumped to a heat exchanger of a steam Rankine cycle for power generation.

In central receiver electricity generation system, collector consists of a large, two-axis tracked field of mirrors (heliostats), which reflect the beam radiation to a centrally placed receiver mounted on the top of a tower. In solar chimney electricity generation system, a flat area exposed to the sun covered by a glass cover. The soil and air underneath the cover will heat up to approximately 35 °C over ambient temperature (greenhouse effect). If the roof is given a slight inclination towards the centre and a high chimney is installed there, the hot air will rise up and wind speed will develop at the entrance of the chimney and this stream can be used for electricity generation by means of wind turbine.

In dish-stirling electricity generation system, the solar collector (paraboloidal dish reflector) and the heat to electricity conversion system (stirling engine), usually a tube or a heat-pipe absorber is placed in the focal point of the dish reflector. A salt gradient solar pond is usually a large reservoir of water with a black bottom absorbing the solar diffuse and beam radiation and transforming it to heat in the form of hot water.

Table 3
Sustainability indicators for solar thermal systems.

S. no.	Year of study	Location	Type	Life time (years)	Power rating (MW)	EPBT (years)	GHG emissions (gCO_{2eq}/kWh_e)	Cost (US cent/kWh_e)
1.	1999 [34]	Australia	Central receiver	NA	100	NA	36.2	NA
2.	2008 [35]	Spain	Central tower	25	17	NA	202	NA
3.	1990 [36]	US	Central receiver	30	100	NA	43	NA
4.	2008 [35]	Spain	Parabolic trough	25	50	NA	196	NA

Table 4
Sustainability indicators for small hydro systems.

S. no.	Year	Location	Type	Life time (years)	Power rating (kW)	GHG emissions (gCO_{2eq}/kWh_e)	EPBT (years)	Cost (US cent/kWh_e)
1.	1996 [39]	Japan	Run-of river	30	10000	18	NA	NA
2.	2008 [40]	India	Run-of river	30	50	74.88	2.71	NA
3.	2008 [40]	India	Run-of river	30	100	55.42	1.99	NA
4.	2008 [41]	India	Run-of river	30	3000	35.29	1.28	NA
5.	2008 [41]	India	Canal-based	30	250	35.35	1.31	NA
6.	2008 [41]	India	Canal based	30	1000	42.98	1.58	NA
7.	2008 [41]	India	Canal based	30	400	33.87	1.26	NA
8.	2008 [41]	India	Dam-toe	30	2000	31.2	1.1	NA
9.	2008 [41]	India	Dam-toe	30	1000	62.4	2.25	NA

In southern Europe both technologies (solar thermal and PV) can operate with cost below 20 euro cents/kWh_e. Solar thermal power plants remain the best cost solution in south Europe and North Africa with possible generation cost below to 10 euro cents/kWh_e. Table 3 shows the sustainability indicators for solar thermal systems.

3.4. Small hydro system

Hydropower is based on a simple process taking the advantage of the kinetic energy freed by the falling water. In all hydroelectric generating stations, the rushing water drives a turbine, which converts the water's motion into mechanical and electrical energy [37]. There is no international consensus on the definition of small hydropower (SHP). The general practice all over the world is to define SHP by power output. Different countries follow different norms keeping the upper limit ranging from 5 to 50 MW. In India, SHP schemes are classified by Central Electricity Authority (CEA) [38]. SHP can be broadly categorized into three different types of scheme, i.e. run-of river, canal based and dam-toe schemes. Table 4 shows the sustainability indicators for small hydro systems.

4. Figure of merit

Figure of merit is generally used to compare the different system based upon their performance, net energy requirement or

Table 5
Figure of merit for renewable based electricity sources.

S. no.	Year	Location	Source	Type	Life time (years)	Power rating (kW)	Cost (US cents/kWh_e)		EPBT (years)		GHG emissions (gCO_{2eq}/kWh_e)		FM
							Cost	Relative	EPBT	Relative	GHG	Relative	
1.	1997	Denmark	Wind	Offshore	20	30	7	9	0.39	10	16.5	10	900
2.	1999	India	Wind	NA	20	1500	7	9	1.0	10	19	10	900
3.	2001	Japan	Wind	Offshore	25	100	7	9	1.4	9	39.4	9	729
4.	2007	Turkey	Wind	Urban area	25	22.5	7	9	1.4	9	20.5	9	729
5.	2006	UK	Solar PV	mc-si	NA	14.4	24	3	8	2	44	8	48
6.	2000	India	Solar PV	c-si	20	0.035	24	3	1.0	10	300	1	30
7.	2000	Italy	Solar PV	c-si	30	3300	24	3	3.2	7	60	8	168
8.	2000	Italy	Solar PV	a-si	30	3300	24	3	2.7	8	50	8	192
9.	1997	Japan	Solar PV	c-si	20	3	24	3	15.5	1	91	6	18
10.	2008	China	Solar PV	c-si	30	100000	19–20	4	1.9	9	12.1	10	360
11.	2006	Singapore	Solar PV	c-si	25	2.7	57	1	4.5	6	165	2	12
12.	2008	China	Solar PV	c-si	30	100000	19–20	4	1.5	9	9.4	10	360
13.	2008	China	Solar PV	a-si	30	100000	19–20	4	2.5	8	15.6	10	320
14.	1999	Australia	Solar thermal	Central receiver	NA	100	20	4	1	10	36.2	9	360
15.	2006	Spain	Solar thermal	Central tower	25	17	20	4	1.02	9	202	1	36
16.	1990	US	Solar thermal	Central receiver	30	100	20	4	1.04	9	43	8	288
17.	2006	Spain	Solar thermal	Parabolic trough	25	50	20	4	1	10	196	1	40
18.	2008	India	Small hydro	Run-of river	30	50	5	10	2.71	8	74.88	7	560
19.	2008	India	Small hydro	Run-of river	30	100	5	10	1.99	9	55.42	8	720
20.	2008	India	Small hydro	Run-of river	30	3000	5	10	1.28	9	35.29	9	810
21.	2008	India	Small hydro	Canal-based	30	250	5	10	1.31	9	35.35	9	810
22.	2008	India	Small hydro	Canal based	30	1000	5	10	1.58	9	42.98	8	720
23.	2008	India	Small hydro	Canal based	30	400	5	10	1.26	9	33.87	9	810
24.	2008	India	Small hydro	Dam-toe	30	2000	5	10	1.1	9	31.2	9	810
25.	2008	India	Small hydro	Dam-toe	30	1000	5	10	2.25	8	62.4	7	560

Range for GHG emissions = 9.4–300; EPBT = 0.39–15.5 and cost = 5–57.

gross carbon emission from the systems [42–43]. In this paper a FM has been proposed to evaluate the different sustainability indicators on single platform by giving them equal weightage. Accounting FM for the selected sustainability indicators, each technology was ranked from 1 to 10 according to the corresponding indicator as shown in Table 5. The maximum value of particular indicator is assigned to be a relative rank 1 while for minimum value it is assigned to be 10, accordingly the distribution has been done from 1 to 10. The value of GHG emissions, EPBT and cost of electricity generation is lower than their respective relative rank value is assigned to be higher. The range for this relative rank parameter is taken as 1–10 from higher values to lower values of GHG emissions, EPBT and cost of electricity generation. The Eq. (4) is used to estimate FM and is given below.

$$\mathrm{FM} = \text{Relative rank}_{\text{cost}} \times \text{Relative rank}_{\text{GHG emisions}} \times \text{Relative rank}_{\text{EPBT}} \quad (4)$$

For calculating FM all the data from different renewable energy sources have been taken from the literature. In some literature, all the three indicators values are analysed but these types of studies are very few. In most of the literature either GHG emissions or energy intensity have been analysed and in some of the literature both energy intensity and GHG emissions or EPBT and GHG emissions have been estimated. With the help of energy intensity, energy pay-back time could be estimated by knowing the life time of the electricity generating plant and the average electricity generation efficiency of that particular country where that particular plant lies. The average electricity generation efficiency is taken as 0.40 for the estimation of EPBT from energy intensity.

The energy intensity (ei) for a plant of power rating (P) and load factor (λ) is defined as the ratio of the energy requirement (E) for construction, operation and decommissioning and the electricity output of the plant over its life time (t) and is shown in Eq. (5) [7].

$$\mathrm{ei} = \frac{E}{P \times 8760 \times \lambda \times t} \quad (5)$$

For the cost estimation very few studies determine the cost of electricity generation of renewable energy sources with their GHG emissions and EPBT analysis. Most of the cost studies are separately done so based upon that wherever; the cost of generation of electricity is not given in the literature, then the average generation cost of electricity is taken from Evans et al. [44] for the determination of figure of merit. Higher the value of figure of merit represents a better renewable electricity generation source. This FM for renewable sources could provide a more rational choice of electricity generation sources for energy planners.

5. Results and discussions

Based upon figure of merit four renewable energy electricity generation sources (wind, PV, solar thermal and small hydro) have been analysed. Table 5 shows the list of FM for these sources having different years of origination, capacity, and their respective life time has been considered for the evaluation of GHG emissions and EPBT. The value of figure of merit for wind, PV, solar thermal and for small hydro varies from 729 to 900, 12 to 360, 36 to 360 and 560 to 900, respectively as shown in Table 6. There is a range of figure of merit for each system that has been studied; this is because of the geography, their life time consideration, capacity of the system, and year of study. As the capacity of the system increases their GHG emissions and EPBT decreases substantially.

This figure of merit suggests that for sustainable electricity generation wind and small hydro systems are to be developed first and after that solar thermal and solar PV systems should be developed. Wind and small hydro systems are very favourable for the sustainable development.

Table 6
Figure of merit range for different renewable electricity generation sources.

S. no.	System	Figure of merit
1.	Wind	729–900
2.	Solar PV	12–360
3.	Solar thermal	36–360
4.	Small hydro	560–900

6. Conclusions

The renewable energy technologies were assessed based on three different sustainability indicators. Each indicator was given an equal importance for the sustainable development and used to rank the renewable energy technologies against their impacts. It has been found out that wind and small hydro renewable electricity generation sources are very well utilised for the sustainable development. In the place (location) where these both options are not available then there development may be focused on solar thermal and solar photovoltaic systems. Although GHG emissions is not only the environmental parameter to be considered there are many more parameters i.e. land use and water uses may also be included for more exhaustive evaluation of figure of merit.

As the invention of new technologies and mass production of these systems will grow, definitely the cost of generation and GHG emissions will go down tremendously. As year of study plays an important role in the figure of merit, initially the cost of generation is higher for these renewable electricity generation sources which are reducing due to advancement in technology and much more efficient systems which are producing.

References

[1] Muneer T, Asif M, Munawwar S. Sustainable production of solar electricity with particular reference to the Indian economy. Renewable Sustainable Energy Rev 2005;9:444–73.
[2] IEA, International energy annual 2004. Energy Information Administration; 2006.
[3] Akella AK, Saini RP, Sharma MP. Social, economical and environmental impacts of renewable energy systems. Renewable Energy 2009;34:390–6.
[4] IEA, World energy outlook 2004. International Energy Agency; 2004.
[5] BP statistical review of world energy. British Petrol; 2003.
[6] Hondo H. Life cycle GHG emission analysis of power generation systems—Japanese case. Energy 2005;30:2042–56.
[7] Lenzen M, Munksgaard J. Energy and CO_2 life-cycle analysis of wind turbines—review and applications. Renewable Energy 2002;26:339–62.
[8] Goralczyk M. Life cycle assessment in the renewable energy sector. Appl Energy 2003;75:205–11.
[9] Tahara K, Kojima T, Inaba A. Evaluation of CO_2 pay back time of power plants by LCA. Energy Convers Manage 1997;38:615–20.
[10] Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy 2006;31(1):55–71.
[11] Kato K, Murata A, Sakuta K. Energy pay-back time and life-cycle CO_2 emission of residential PV power system with silicon PV module. Prog Photovoltaics Res Appl 1998;6:105–15.
[12] Krohn S. The energy balance of modern wind turbines. Wind Power Note 1997;16:1–16.
[13] Awerbuch S. Investing in photovoltaics: risk, accounting and the value of new technology. Energy Policy 2000;28:1023–35.
[14] Moran D, Sherrington C. An economic assessment of windfarm power generation in Scotland including externalities. Energy Policy 2007;2207(35):2811–25.
[15] Ito M, Kato K, Komoto K, Kichimi T, Kurokava K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale (VLS-PV) systems in deserts using m-si, a-si, CdTe and CIS modules. Prog Photovoltaics Res Appl 2008;16:17–30.
[16] Kannan R, Leong KC, Osman R, Ho HK, Tso CP. Life cycle assessment study of solar PV systems: an example of a 2.7 kWp distributed solar PV system in Singapore. Solar energy 2006;80(5):555–63.
[17] Sims REH, Rogner HH, Gregory K. Carbon emission and mitigation cost comparison between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy policy 2003;31:1315–26.

[18] European Wind Energy Association (EWEA) 2005. EU wind capacity map (http://www.ewea.org).
[19] Alpinar EK, Alpinar S. An investigation of wind power potential needed in installation of wind energy conversion systems.. Proc IMechE A J Power Energy 2006;220:1–13.
[20] Mathew S. Wind energy: fundamentals, resource analysis and economics. Berlin, Heidelberg: Springer; 2006.
[21] Elhadidy MA, Shaadid SM. Promoting applications of hybrid (wind + photovoltaics + diesel + battery) power systems in hot regions. Renewable Energy 2004;29(4):517–28.
[22] Schleisner L. Life cycle assessment of a wind farm and related externalities. Renewable Energy 2000;20:279–88.
[23] Uchiyama Y. Life cycle analysis of photovoltaic cell and wind power plants. In: Assessment of greenhouse gas emission from the full energy chain of solar and wind power and other energy sources. Vienna (Austria): IAEA; 1996.
[24] Gurzenich D, Mathur J, Bansal NK, Wagner HJ. Cumulative energy demand for selected renewable energy technologies. Int J LCA 1999;4(3):143–9.
[25] Proops JLR, Gay PW, Speck S, Schroder T. The life time pollution implications of various types of electricity generation. Energy Policy 1996;24(3): 229–37.
[26] Nomura N, Inaba A, Tonooka Y, Akai M. Life cycle emission of oxidic gases from power generation systems. Appl Energy 2001;68:215–27.
[27] Celik AN, Muneer T, Clarke P. An investigation into micro wind energy systems for their utilization in urban areas and their life cycle assessment. Proc IMechE A Power Energy 2007;221:1107–17.
[28] Celik AN, Muneer T, Clarke P. Optimal sizing and life cycle assessment of residential photovoltaic energy systems with battery storage. Prog Photovoltaics Res Appl 2008;16:69–85.
[29] Muneer T, Younes S, Lambert N, Kubie J. Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location. Proc IMechE A Power Energy 2006;220:517–24.
[30] Mathur J, Bansal NK, Wagner HJ. Energy and environmental correlation for renewable energy systems in India. Energy Sources 2002;24:19–26.
[31] Alsema EA. Energy pay back time and CO_2 emissions of PV systems. Prog Photovoltaics Res Appl 2000;8:17–25.
[32] Prakash R, Bansal NK. Energy analysis of solar photovoltaic module production in India. Energy Sources 1995;17:605–13.
[33] Trieb F, Langnib O, Klaib H. Solar electricity generation-comparative view of technologies, costs and environmental impact. Solar Energy 1997;59(1–3): 89–99.
[34] Lenzen M. Greenhouse gas analysis of solar-thermal electricity generation. Solar energy 1999;65(6):353–68.
[35] Lechon Y, Rua C, de la Saez R. Life cycle environmental impacts of electricity production by solar thermal power plants in Spain. J Solar Energy Eng ASME 2008;130:0210121–210127.
[36] Kreith F, Norton P, Brown D. A comparison of CO_2 emissions from fossil and solar power plants in the US. Energy 1990;15(12):1181–98.
[37] Egre D, Milewski JC. The diversity of hydropower projects. Energy Policy 2002;30:1225–30.
[38] CEA, Guidelines for development of small hydro electric scheme, Government of India, New Delhi; 1982.
[39] Gagnon L, Vate JFV. Greenhouse gas emissions from hydropower. Energy policy 1997;25(1):7–13.
[40] Varun, Bhat IK, Prakash R. Life cycle analysis of run-of river small hydro power plants in India. Open Renewable Energy J 2008;1:11–6.
[41] Varun, Bhat IK, Prakash R. Life cycle energy and GHG analysis of small hydro electric power development in India, Int J of Green Energy, submitted for publication.
[42] Prakash R, Henham A, Bhat IK. Net energy and gross pollution from bioethanol production in India. Fuel 1998;77(14):1629–33.
[43] Mullick SC, Kandpal TC, Kumar S. Testing of box-type solar cooker: second figure of merit F_2 and its variation with load and number of pots. Solar Energy 1996;57(5):409–13.
[44] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renewable Sustainable Energy Rev 2009;13(5):1082–8.